The Principal Axis of the Virgo Cluster

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ABSTRACT

Using accurate distances to individual Virgo cluster galaxies obtained by the method of Surface Brightness Fluctuations, we show that Virgo's brightest ellipticals have a remarkably collinear arrangement in three dimensions. This axis, which is inclined by $\sim 10 - 15°$ from the line of sight, can be traced to even larger scales where it appears to join a filamentary bridge of galaxies connecting Virgo to the rich cluster Abell 1367. The orientations of individual Virgo ellipticals also show some tendency to be aligned with the cluster axis, as does the jet of the supergiant elliptical M87. These results suggest that the formation of the Virgo cluster, and its brightest member galaxies, have been driven by infall of material along the Virgo-A1367 filament.

Subject headings: galaxies: clusters: individual (Virgo), galaxies: formation, cosmology: large-scale structure of universe

1. Introduction

The Virgo cluster, at a distance of approximately $15\,h^{-1}$ Mpc, is the nearest richly-populated cluster of galaxies and, consequently, one of the best studied. A number of authors have pointed out that Virgo's brightest elliptical galaxies have a remarkably linear arrangement, along a projected position angle of roughly 110° (measured North through East). Arp (1968), for example, noted that "all the E galaxies in the northern half of the Virgo cluster fall on a line going through M87." Similarly, Binggeli, Tammann & Sandage (1987) suggested that "The line connecting M87 and M84 appears as a fundamental axis of the cluster." This can be seen in Figure 1, which plots the distribution of probable member galaxies in the northern portion of the Virgo cluster, as seen on the plane of the sky. The distribution of Virgo dwarf elliptical galaxies also appears somewhat elongated in this direction (Binggeli 1999), as does the distribution of hot X-ray emitting intracluster gas (Böhringer et al. 1994; Schindler, Binggeli & Böhringer 1999). However, without accurate distances to individual galaxies, it is impossible to say for certain whether Virgo's apparent principal axis is a genuine three-dimensional structure, or merely an illusory chance alignment of galaxies. Furthermore, three-dimensional information would allow one to measure the true shape and spatial orientation of this axis.

Here we present evidence that Virgo's bright elliptical galaxies trace a highly elongated, three-dimensional structure that is actually a small segment of a much larger filament passing through the heart of the Virgo cluster.

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2. Resolving the Virgo Cluster in Three Dimensions

A variety of methods exist for measuring galaxy distances (see Jacoby et al. 1992 for a review). One of the most powerful is the technique of Surface Brightness Fluctuations (hereafter SBF), whereby distances to galaxies are estimated from the ratio of the second and first moments of their stellar luminosity functions (Tonry & Schneider 1988; see Blakeslee, Ajar & Tonry 1999 for a recent review). This method works best for early-type galaxies, although it has also been applied to the bulges of some spirals. Ferrarese et al. (2000) have concluded that SBF is the most accurate early-type galaxy distance indicator reaching cosmologically interesting distances.

Tonry et al. (2000) have recently published SBF distances for 300 nearby galaxies that were observed as part of their I-band SBF Survey. Based on distances for 31 probable Virgo cluster members, they derived a mean cluster distance modulus $m - M = 31.15 \pm 0.03$, corresponding to a distance of 17 ± 0.3 Mpc. Uncertainties in individual Virgo galaxy distances are $\sim 1.5 - 2$ Mpc, which suggests that it should be possible to resolve the Virgo cluster along the line of sight, at least partially. Indeed, Tonry, Ajhar, Luppino (1990) attempted to do this a decade ago, but they lacked a suitable calibration. They assumed that the I-band SBF magnitude $\overline{m}_I$ was insensitive to stellar population variations among ellipticals, as implied by the best population models at the time. As a result, they essentially found that bluer Virgo ellipticals were systematically in front of redder ones. Following a decade of work, the stellar population dependence of $\overline{m}_I$ has been empirically well characterized and calibrated out (Tonry et al. 1997; Ferrarese et al. 2000), so that there is no longer any correlation of the distances with stellar population parameters. Moreover, the empirical calibration now has strong support from theoretical modeling (Worthey 1994; Liu et al. 2000; Blakeslee, Vazdekis, & Ajhar 2000).

Table 1 lists data for all elliptical galaxies in the northern portion of the Virgo cluster with SBF distances from the Tonry et al. (2000) survey. Column (1) gives the galaxy name, column (2) lists the SBF distance of each galaxy from Tonry et al. (2000), and column (3) gives the orientation of the galaxy major axis, taken from the Lyon-Meudon Extragalactic Database (LEDA). The positions and distance moduli of these galaxies are also indicated in Figure 2.

Table 1 and Figure 2 suggest some tendency for those galaxies located in the western region of the cluster to be more distant than those on the eastern side. This trend can be seen more clearly in Figure 3, which shows a clear correlation between galaxy right ascension and distance, with a systematic trend of increasing galaxy distance as one moves in the westerly direction. Pearson (parametric) and Spearman (non-parametric) rank correlation tests both confirm that this trend is statistically significant, at the 97% and 99% confidence levels, respectively (the correlation becomes even stronger if NGC 4168 is also included). We note that Neilsen & Tsvetanov (2000) have recently measured independent SBF distances with the *Hubble Space Telescope* for 15 Virgo galaxies, including 10 ellipticals along this central ridge line, and have observed the same trend in their data.

To measure the three-dimensional shape and orientation of this axis, we computed the moments of inertia of the system of galaxies in Table 1 after converting their right ascensions, declinations and distances to supergalactic cartesian coordinates. Diagonalization of the inertia tensor yields the three eigenvalues corresponding to the principal moments of inertia, and the associated eigenvectors provide information on the orientation of the principal axis.

We find that the Virgo ellipticals have a remarkably collinear arrangement in three-dimensions, with an *rms* scatter of only ~ 400 kpc about the principal inertial axis along its ~ 8 Mpc length between NGC 4387 and NGC 4660. This axis is inclined at an angle of approximately $\sim 75° - 80°$ with respect to the plane of the sky, i.e., close to the line of sight. Presumably with smaller distance uncertainities, Virgo's principal axis would be found to be even narrower.

3. Galaxy Orientations in Virgo

Additional evidence of the special nature of the axis defined by Virgo's brightest ellipticals comes from the orientations of the galaxies themselves. As Table 1 shows, the majority have projected major axis position angles between 100° and

140°, quite similar to the 110° projected orientation of the cluster principal axis. A Kolmogorov-Smirnov (KS) test indicates a probability of only $\sim 7\%$ that the galaxy position angles in Table 1 are randomly-oriented between 0 and 180 degrees. While one must be cautious not to overinterpret the statistical significance of results based on a small sample like this, nevertheless it is suggestive that the orientations of Virgo's large ellipticals may be somehow related to the direction of the cluster principal axis. A similar alignment effect is seen for the brightest elliptical galaxies in the Coma cluster (West 1998), as well as other clusters (Binggeli 1982; Porter, Schneider & Hoessel 1991; West 1994) and references therein.

To test whether fainter Virgo ellipticals might also have preferred orientations with respect to the cluster major axis, we used the Virgo Photometry Catalogue (VPC) of Young & Currie (1998), which provides data, including orientations, for 1180 galaxies in the core region of the cluster. Because the VPC includes both Virgo members and unrelated galaxies along the line of sight, we cross-correlated it with the list of probable Virgo members from Binggeli, Sandage & Tammann (1985) to produce a sample of 108 Virgo ellipticals with measured major axis position angles. Application of the KS test to this sample shows no statistically significant tendency for the fainter ellipticals to have preferred orientations. However, when the roundest galaxies – whose position angles are most uncertain – are eliminated by restricting the sample to only those with ellipticities greater than 0.2, then the KS test indicates that this subset of 69 galaxies has only a $\sim 4\%$ probability of being consistent with a randomly orientated population, with a median galaxy position angle of 107°.

4. A Link Between Virgo and the A1367-Coma Supercluster?

One of the most striking features of the large-scale distribution of galaxies is its filamentary appearance, with long, quasi-linear arrangements of galaxies that extend tens or perhaps even hundreds of Mpc in length. Given the linear arrangement of galaxies along Virgo's principal axis, it is natural to ask whether this might be related to filamentary features on larger scales.

As viewed on the plane of the sky, Virgo's principal axis points in the direction of Abell 1367, a rich cluster located some $75\,h_{75}^{-1}$ Mpc away along a projected position angle of 125°. A1367 itself forms part of a well-known supercluster with the Coma cluster (Gregory & Thompson 1978; de Lapparent, Geller & Huchra 1986). This raises the intriguing possibility that the Virgo, A1367 and Coma clusters may all be members of a common filamentary network, an idea suggested two decades ago by Zeldovich, Einasto & Shandarin (1982).

Figure 4 plots the distribution of nearby poor galaxy clusters from the catalog of White et al. (1999). A narrow bridge of material is clearly seen connecting Virgo and A1367. Furthermore, the chain of giant elliptical galaxies that defines Virgo's principal axis appears to be a segment of this filament. Hence, the Virgo cluster points towards A1367, not only in two dimensions, but in three. Additional indirect evidence of a Virgo-A1367 connection comes from A1367's orientation; X-ray observations show that this cluster is very elongated along a projected position angle of $\sim 140°$ (Jones & Forman 1999), and thus in the general direction of the Virgo cluster.

Of course, the Virgo cluster is often considered part of the larger supercluster which includes Hydra-Centaurus and Pavo-Indus (e.g., Tully 1986). Lynden-Bell et al. (1988) viewed this extended, planar supercluster complex as centered on the "Great Attractor," with Virgo near the outskirts. Thus, we can now trace an apparent link between two of the most massive structures in the local universe: from the "Great Wall" encompassing the Coma cluster to the Great Attractor, through A1367 and the Virgo cluster.

5. Conclusion

We have shown that the brightest elliptical galaxies in the Virgo cluster have a remarkably collinear arrangement in three dimensions. This axis appears to be part of a larger filament connecting the Virgo cluster to Abell 1367. Virgo's elliptical galaxies also exhibit a tendency for their major axes to share this same orientation.

Cosmological N-body simulations show that clusters of galaxies often form at the intersection of filaments, with material flowing into the cluster along one or more axes (van Haarlem & van de Weygaert 1993; Bond, Kofman & Pogosyan 1996). Built by a series of subcluster mergers that occur along preferred directions, clusters naturally develop major axis orientations that reflect the orientation of the dominant filament feeding them (West, Jones & Forman 1995). Furthermore, if large elliptical galaxies are products of galaxy mergers, then the highly anisotropic nature of the merger process will tend to produce ellipticals whose major axis orientations are also aligned with the surrounding filamentary structure (West 1994; Dubinski 1998).

The results presented here are consistent with a picture in which the formation of the Virgo cluster and its elliptical galaxy population has been driven by anisotropic inflow of material along the Virgo-A1367 filament. Although Virgo may be fed by more than one filament (Tully 1982), the one joining the cluster to A1367 appears to dominate. Additional evidence in support of this interpretation comes from X-ray observations of M86, which show a plume of hot gas being stripped from this galaxy along a projected position angle of $\sim 110°$ (Forman et al. 1979), presumably as a result of ram pressure as the galaxy travels along the cluster principal axis at over 1200 km^{-1} s.

Finally, it is intriguing that M87's famous jet also emanates along the same direction as the Virgo cluster major axis. This is true not only in two dimensions, where both are oriented along projected position angles of $\sim 110-120°$, but also in three dimensions. Detailed models of the jet's observed properties indicate that it is most likely oriented within ~ 20 degrees of the line of sight (Heinz & Begelman 1997; Biretta, Sparks & Macchetto 1999), very close to the 10° to 15° line of sight inclination angle of the cluster principal axis found in §2. While this might be purely coincidental, alternatively, it might be an indication that Virgo's principal axis has influenced not only the orientations of its member elliptical galaxies, but perhaps even the massive blackhole at the center of M87 that is believed to power its nuclear activity (West 1994).

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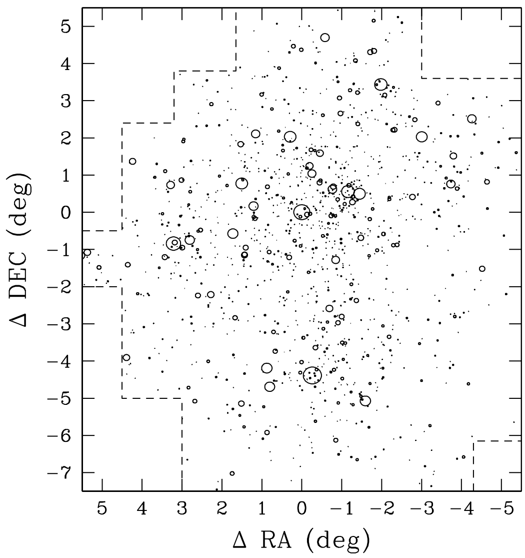

Fig. 1.— A map of the distribution of likely member galaxies in the Virgo cluster, taken from the catalogue of Binggeli, Sandage & Tammann (1985). Galaxy positions are measured relative to NGC 4886 (M87). The area of each symbol is proportional to galaxy luminosity. The dashed lines indicate regions not included in the Binggeli et al. survey. As discussed in the text, the brightest galaxies in the northern part of the cluster form a chain oriented along a projected position angle of ~ 110 degrees.

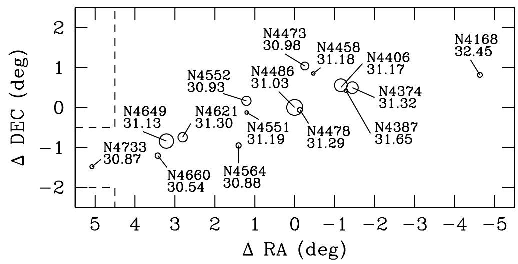

Fig. 2.— A plot of those elliptical galaxies in the northern half of the Virgo cluster for which SBF distances are available from the survey of Tonry et al. (2000). We have also included NGC 4168 which, although not a Virgo member, lies in the field of view and also has a measured SBF distance.

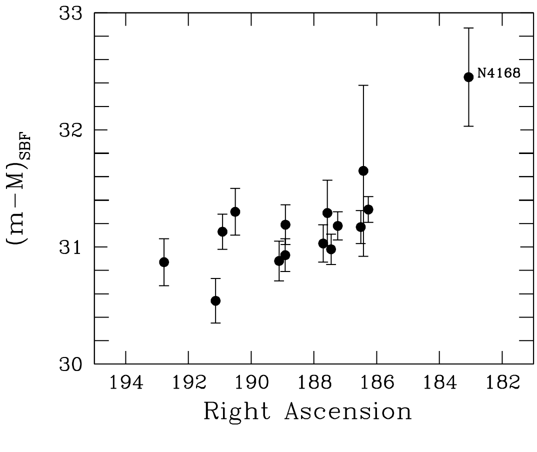

Fig. 3.— Right ascension versus SBF distance modulus for the Virgo ellipticals in Table 1. NGC 4168 is also indicated.

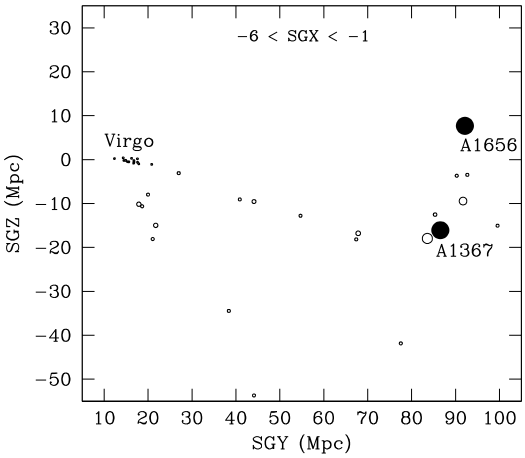

Fig. 4.— The distribution of poor clusters in a $5\,h_{75}^{-1}$ Mpc thin slice centered on the Virgo cluster. Supergalactic coordinates SGY and SGZ are plotted. The poor cluster sample is taken from White et al. (1999). Cluster distances are based on the mean redshift of all members. Only clusters with $\langle z \rangle \geq 0.005$ were used, to ensure that peculiar velocities are small enough relative to Hubble expansion that accurate distances could be obtained from the Hubble law. The area of each symbol is proportional to the number of galaxies belonging to the group. Virgo ellipticals listed in Table 1 are also plotted as individual points. A narrow bridge of material is seen connecting the Virgo cluster with A1367.

Table 1
Virgo Cluster Ellipticals.

Galaxy	$(m-M)_{SBF}$	PA (deg)
NGC 4374 (M84)	31.32 ± 0.11	135
NGC 4387	31.65 ± 0.73	140
NGC 4406 (M86)	31.17 ± 0.14	130
NGC 4458	31.18 ± 0.12	46
NGC 4473	30.98 ± 0.13	100
NGC 4478	31.29 ± 0.28	140
NGC 4486 (M87)	31.03 ± 0.16	160
NGC 4551	31.19 ± 0.17	70
NGC 4552 (M89)	30.93 ± 0.14	125[a]
NGC 4564	30.88 ± 0.17	47
NGC 4621 (M59)	31.31 ± 0.20	165
NGC 4649 (M60)	31.13 ± 0.15	105
NGC 4660	30.54 ± 0.19	100
NGC 4733	30.87 ± 0.20	115

[a]With the exception of NGC4552, all major axis position angles are taken from the Lyon-Meudon Extragalactic Database (LEDA). No PA was listed for NGC4552 in LEDA, and so we adopted a value of 125° from the study by Carollo et al. (1997; see also King 1978).